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Early Performance of Eight Experimental Cathodic Protection Systems at the Burlington Skyway Test Site

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All eight systems are being monitored and the data collected through July 1984 is presented. All the impressed current systems were found to be effective in stopping corrosion, but the components of some systems are not sufficiently durable. Insufficient power was available from the galvanic system for it to be practical. The future work required to develop a full scale operational cathodic protection system for bridge substructures is discussed.

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EARLY PERFORMANCE OF EIGHT EXPERIMENTAL CATHODIC PROTECTION SYSTEMS AT THE BURLINGTON BAY SKYWAY TEST SITE

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ABSTRACT

The paper describes the initial phases of a research program to develop an effective cathodic protection system for use on bridge substructures.

Four experimental cathodic protection systems were installed on the columns of the Burlington Bay Skyway Bridge in 1982 and four more were added in 1983. Seven were impressed current and one was a galvanic system. Each system covered approximately 40 m^2 of concrete surface. Several types of instrumentation were developed to monitor the effectiveness of the cathodic protection.

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INTRODUCTION

Four experimental cathodic protection systems were installed on the columns of the Burlington Bay Skyway in 1982 and four more were added in 1983. The project is part of a research program to develop a means of rehabilitating corrosion-damaged bridge substructures. The specific objectives of this project and the details of the test site have been described in two earlier papers (1,2). This paper summarizes the important features of each system and their performance through to July 1984.

DESIGN AND CONSTRUCTION

With the exception of System 4, all the installations were impressed current systems. Each impressed current system was powered by an unfiltered, full wave rectifier operating under constant current control. A summary of the main features of each system is given in Table 1 and a more complete description follows.

Systems 1 to 4 were installed in the same configuration; three panels high on the south column face and two panels high on the remaining faces. This was done to determine if protection of the third panel on the south face influenced corrosion activity over the adjacent unprotected faces. A "panel" refers to the area of one face between adjacent rustication strips. The rustication strips, which were at 1.22 m centers are visible in Figure 1. Systems 5 to 8 were installed three panels high on all four faces.

Prior to installing the cathodic protection systems, the areas of delaminated concrete were removed and patched; all the surfaces were sandblasted and any exposed metal form ties were coated with epoxy.

An individual connection was made to each anode so that they could be powered independently to investigate different anode spacings.

System 1

Precast conductive polymer anodes were placed vertically on 450 mm centers as shown in Figure 1. The conductive polymer consisted of a vinyl ester binder with spherical carbon particles providing a specified resistivity of less than 10 ohm cm. Two strands of 30,000 filament carbon fiber were embedded the full length of each anode to increase conductivity. The fiber was made from a polyacrylonitrile (PAN) base. The anodes were cast by Ministry staff. The entire system was covered with a conventional portland cement shotcrete overcoat, nominally 40 mm thick.

System 2

The primary anodes were the same as in System 1 except that a single strand of platinized niobium copper core wire was embedded the full length of each anode. The anodes were placed horizontally on the column, connected at the corners to form three "rings" around the column at the level of the rustication strips.

A secondary anode of water-based graphite-pigmented conductive paint was placed on the surface of the panels bordered by the anodes. The paint had low resistance and promising durability characteristics, although it was not developed specifically for use on exterior concrete surfaces.

System 3

This design utilized the same primary anodes used in System 2. The anodes were placed vertically with two anodes at the third points of the long faces and one anode at the center of the short faces as shown in Figure 1. A secondary anode of carbon fiber was applied to form a network on the concrete surfaces. The fiber on each face was continuous, but there was no connection between adjacent faces. The south and west faces used a double strand of the 30,000 filament PAN fiber described in System 1. A 20,000 filament pitch-based fiber overbraided with dacron was used on the north and east faces. The entire system was covered with 40 mm of conventional portland cement shotcrete.

System 4

This was the only sacrificial anode, or galvanic, system. Work elsewhere (3,4) had shown that various configurations of zinc anodes could provide adequate protection to steel reinforcement in concrete. The anodes used were in the form of a diamond-shaped (9 mm x 12 mm) zinc ribbon with steel core by which connections to the anode could be made. The anodes were placed vertically on 150 mm centers. All the anodes on each face were connected

to a single feeder cable which was connected, through a switch, to the reinforcement on the same face. The entire system was given a 40 mm thick shotcrete overcoat. Salt was added to the shotcrete to reduce its resistance and also to ensure that the potential of the zinc remained active.

System 5

System 5 utilized a proprietary long line conductive polymer anode recently introduced to the marketplace. It was used in combination with a 40 mm thick shotcrete overcoat. The anode was supplied in the form of an expandable mesh as shown in Figure 2. The length of anode on each face was 13.4, 10.7, 12.4 and 8.7 m per m^2 of concrete surface for the north, south, east and west faces respectively.

System 6

Like System 2, System 6 employed a conductive coating as a secondary anode. The coating consisted of graphite in an acrylic solution. The primary anodes on the north and west faces were polymer concrete; graphite anodes were used on the other two faces. The anodes were attached by mechanical anchors and cemented to the column with poured-in-place conductive polymer to ensure a good electrical connection. The polymer concrete anodes were precast by the manufacturer and had a platinized wire core. The paint was chosen for use on the basis that it had been identified as having superior durability properties in an ongoing study under the National Cooperative Highway Research Program

in the U.S. Its resistivity was higher than that of the paint used in System 2.

The east and west faces were given two coats of latex paint to investigate the effect of an overcoat on the response of the system to changes in the moisture content of the environment. A view of the completed installation is shown in Figure 3.

System 7

This system utilized the same 30,000 filament PAN carbon fiber used in System 3. Three faces of the column were covered with a mesh made up of fibers on a 75 mm grid spacing as shown in Figure 4. The north face employed a fiberglass mesh with carbon fiber interwoven vertically on 25 mm centers. Precast conductive polymer anodes were used on the south and east faces. Platinized wire, covered by poured-in-place polymer concrete was used for the primary anodes on the other two faces. The entire system was covered with shotcrete.

System 8

System 8 was a proprietary system consisting of primary anodes of platinized wire embedded in a conductive paste and a secondary anode of a carbon-filled, water-based acrylic paint. Single vertical anodes were placed in the center of three of the column faces and two vertical anodes were placed at the third points of the west face as shown schematically in Figure 5. A latex paint overcoat was applied to the north, east and west faces.

A tie coat was also used between the conductive paint and the overcoat on the north face to improve the bond between the two.

INSTRUMENTATION

After reviewing the experience of others (5,6), instrumentation consisting of macrocells, reference cells, current pick-up probes, current distribution probes, and electrical resistance probes was designed and installed in Systems 1 to 4.

The macrocell is a strong natural corrosion cell in which current flow can be measured. The ability of the cathodic protection to reverse the direction of current flow (i.e. stop corrosion) is one indication of its effectiveness. A zinc-zinc sulfate reference cell and a thermocouple were embedded adjacent to each macrocell. The current pick-up probes consisted of short pieces of rebar embedded at the level of the reinforcing steel at various points in the structure. They were used to measure current density. The current distribution probes consisted of three current pick-up probes installed at the same locations but at different depths from the concrete surface. They were used to measure the variation of current density with depth. The electrical resistance probes were designed to give a quantitative measurement of corrosion in terms of metal loss per year.

The instrumentation and anode leads were terminated in a single junction box for each system. All the measurements were made at the junction box. Details of the fabrication and installation

of the instrumentation is given in Reference 1 and the method of making measurements in Reference 2.

The instrumentation used in Systems 5 to 8 was modified following one year's experience in monitoring Systems 1 to 4. The changes were as follows:

1. The electrical resistance probes did not function satisfactorily in Systems 1 to 4 and were not used.
2. The current distribution probes in Systems 1 to 4 gave very consistent data. It was decided there was no reason to repeat the measurements in Systems 5 to 8.
3. Fewer macrocells were constructed in order to reduce installation costs.
4. In addition to the zinc-zinc sulfate reference cells, molybdenum-molybdenum oxide, silver-silver chloride, lead and carbon cells were installed in System 5. Silver-silver chloride and molybdenum-molybdenum oxide cells were also installed in System 6 and Systems 7 and 8 respectively. In all cases, the additional reference cells were installed adjacent to the reinforcing steel but not adjacent to the macrocells. The number and location of the various types of instrumentation for a typical system are shown in Figure 5.

Throughout this paper, the convention used was to attach the positive lead of the voltmeter to ground. Using this procedure, a positive meter reading indicated that a probe (macrocell,

pick-up or distribution) is anodic (i.e. corroding). Conversely, negative readings indicate that a probe is cathodic (i.e. non-corroding). Resistance measurements were made with a Vibroground Model 263 meter. A Beckman Model 3010 meter was used for current and voltage readings and a Nicolet Model 3091 oscilloscope was used to measure the reference cell potentials.

OPERATION

Systems 1 to 4 were activated in October 1982. E-log I tests were conducted in order to determine the current required for protection according to the procedures given in References 2 and 7. The tests yielded an average protection current value of 418 mA, with values ranging from 250 to 780 mA. For purposes of comparison, the three impressed current systems (1,2 and 3) were all set at a constant current of 500 mA. This current level has been maintained (except when the systems have been intentionally switched off) throughout the monitoring period described in this report. The sacrificial anode system was activated by connecting the anodes to the column reinforcing steel and had an initial driving voltage of approximately 300 mV.

Systems 5 to 8 were powered in November 1983. They were powered to maintain the same average current density (13 mA/m^2 of concrete surface) as Systems 1 to 3. Since the areas of these systems were not the same, as shown in Table 1, the current requirements also differed.

All the systems were switched off periodically for several days to several weeks and allowed to depolarize in order to observe depolarization characteristics. Different anode configurations were investigated in several of the systems.

RESULTS OF MONITORING PROGRAM

A summary of data collected from Systems 1 to 4 and Systems 5 to 8 during the November 1982 to July 1984 monitoring period reported here is given in Tables 2 and 3 respectively. Current densities in each system, in terms of concrete surface area, and the proportion of current flowing to each column face or anode region are shown. The average of the current shifts experienced during all the operating periods is given for the current pick-up probes and the macrocell probes in each system, in terms of current density on the probe surface. High and low values of anode-to-rebar resistance are also shown. These results and other pertinent data are discussed in more detail in the following sections.

Impressed Current Systems

1. Voltage

One requirement for satisfactory performance of a cathodic protection installation is that the protection current be maintained at an acceptable voltage level. For the three impressed current systems installed in 1982, voltages were typically in the range of 3 to 6 V. Voltage levels were seen to vary in response to changes in temperature and humidity. Systems 1 and 3, with shot-

crete overcoats, were generally stable and responded slowly to these changes. They exhibited slightly higher voltages during the winter months of 1983 and 1984, corresponding to increases in anode-to-ground resistance.

System 2 showed rapid and extreme responses to changes in temperature and humidity. Driving voltages of 13 to 14 V were experienced during the summer months in both 1983 and 1984, corresponding to periods of high anode-to-ground resistance in this system. Both poor mechanical contact between anode and paint, and drying of the concrete surface below the paint, contributed to this increased resistance. The system voltage dropped sharply in the fall of 1983, returning to the previous level of approximately 3 V, and remained there until the spring of 1984.

Voltage levels in Systems 5 to 8 during their initial nine months of operation typically ranged between 2 and 6 V. In all four systems, higher voltages were required during cold periods to maintain the constant system currents. In contrast with System 2, Systems 6 and 8, which also employed conductive paint anodes, showed no significant increase in voltage levels during hot dry periods.

Typical values of operating voltage for all eight systems are shown in Figure 6. For systems in which voltage levels during winter and summer differed significantly, average voltages are

shown for each period, denoted in Figure 6 by W and S respectively.

2. Macrocells

The initial application of cathodic protection current was sufficient in all the impressed current systems to reverse current flow in the macrocells. That is, under cathodic protection, the corroding anode of the macrocell became a current-receiving cathode.

Average macrocell current shifts are shown for all eight systems in Tables 2 and 3. Where current shifts seen in winter and summer differed significantly, they are shown separately, denoted W and S as above.

Typical macrocell data is shown in Figure 7, which is a plot of the current density on three of the macrocell probes in System 2 as a function of time during the seven months following cell installation. Probe 2 was located outside the protected area and served as a control, remaining anodic through the monitoring period. In contrast to it, Probes 1 and 5 were cathodic during periods when current was applied but shifted in the anodic direction when the power was switched off.

Although the data shown in Figure 7 can be considered typical, some macrocells did not remain cathodic at all times. This

usually occurred during periods of hot weather when the cells were more active, or was associated with obvious areas of degradation of the anode in some of the systems.

There were also indications of long term changes in macrocell behavior, which may or may not be attributable to the application of cathodic protection. The shift in current density between consecutive off and on periods gradually decreased. Eventually some macrocells remained cathodic even though other cells in the same system became anodic during periods of depolarization. This may indicate a decrease in the required protection current with time or migration of chloride ion away from the macrocell probe, which reduces the intensity of the galvanic cell. However, the control cells outside the limits of the cathodic protection in Systems 1 to 4 also showed decreasing current with time, although they continued to corrode whether the power was on or off. This makes the data more difficult to interpret and suggests that macrocells may be most useful as a monitoring tool shortly after installation, but become less reliable at later ages.

3. Current Pick-up Probes

The current density of 13 mA/m^2 applied to the concrete surface corresponds to an average of approximately 2.8 $\mu A/cm^2$ on the surface of the reinforcing steel. This figure was calculated based on all the steel in the protected areas and includes two layers of main reinforcement. Current densities in all the impressed current systems on probes embedded at the level of

the first layer of reinforcement were typically in the range of -2 to -6 $\mu A/cm^2$ during periods when power was applied. During "off" periods, current flow to or from the pick-up probes was essentially zero. In contrast with the macrocell probes, there was no significant change from one "off" period to another.

The pick-up probes were also used to measure the uniformity of current flow within each system. System 1, with closely spaced primary anodes, and System 2, with a conductive paint secondary anode covering the surface, both showed an even distribution of current. Probe current densities were in the range of -1 to -4 $\mu A/cm^2$. In System 1, current densities decreased slightly as the distance from the supply end of the anode increased. This effect was not seen in System 2, indicating that the paint system provided superior current distribution. The magnitude of current densities measured in System 3 was higher than seen in Systems 1 and 2, ranging from -4 to -8 $\mu A/cm^2$. Highest densities occurred directly beneath primary anodes, decreasing midway between anodes and reaching a minimum midway between anodes and column edges as shown in Figure 8. These minimum levels were comparable to values seen in Systems 1 and 2.

Current distribution in System 5 beneath the surface anode mesh was uniform throughout the system with an average current density on the pick-up probes of -3.2 $\mu A/cm^2$. Anodes on each face were initially powered from both ends, with an insulated wire interconnecting the anode mesh at approximately every fourth loop

along the bottom of the mesh. This was done in order to introduce a degree of redundancy into the system and to ensure that later investigative coring of the concrete would not result in electrical isolation of portions of the mesh. This arrangement can be seen in Figure 2. It was found that it was sufficient to power each mesh from one end only as this caused no decrease in current densities or increase in driving voltage.

In System 6, current densities were relatively high, averaging $-6.1\ \mu A/cm^2$. There was considerable variation over the system, with the highest densities experienced in the vicinity of the anodes and on the narrower north and south faces where the anodes were spaced 2.0 m apart. Very low densities were seen at the mid-points of the longer faces which suggest that for this material a primary anode spacing of 3.8 m is too large.

System 7 had a relatively even current distribution over its surface. However, average surface current density on the north column face, with its fiberglass/carbon fiber anode, was approximately one half the average current density on the other three faces ($-8.0\ mA/m^2$ and $-14.5\ mA/m^2$ respectively). This corresponds to a higher anode-to-ground resistance for this face.

Initially, the current distribution in System 8 was very uniform with an average current density on the pick-up probes of $-5.2\ \mu A/cm^2$. There was a definite decrease in current densities experienced during the May-July period of 1984, compared to the

preceding winter. This was particularly evident on the south and west faces corresponding to visible evidence here of anode deterioration on those faces. As the conductive paint anode on the south face was broken down, probes in the affected areas no longer received current (this is discussed in more detail in the section on Durability).

Alternative anode spacings were investigated in five of the systems. In System 1, alternate anodes were powered resulting in a doubling of anode spacing to 900 mm. In System 3, one primary anode was used to power a maximum length of 4.0 m of carbon fiber. These increased anode spacings resulted in unacceptable decreases in system current densities. In System 2, it was found that anode separation could be doubled to 2.5 m without a significant decrease in protection levels. System 7 was powered, for a short length of time, by one anode per face rather than two. This resulted in an extremely uneven distribution of current over the system which was unacceptable. The positions of the anodes in System 8 were such that spacings of 2.8 m and 3.7 m could be investigated by disconnecting appropriate anodes. The current density on the probes was maintained for the 2.8 m spacing but at 3.7 m, current densities on probes remote from the anode dropped substantially, indicating that the optimum anode spacing is in the range of 2.5 to 3.0 m.

4. Current Distribution Probes

The current distribution probes installed in Systems 1, 2 and

3 were designed to measure the variation of current density with depth compared with the current pick-up probes which were used to measure the uniformity of current over the concrete surface. The average results for the period October 1982-April 1983 for all the probes embedded at the 100, 180, and 250 mm depths in Systems 1, 2 and 3 are given in Figure 9. Thus the probes at the 250 mm depth received 15 percent of the current reaching the probes at the 100 mm depth even though the deeper probe was at a greater depth than the two layers of main reinforcement. The measurements showed that even deeply embedded steel received some beneficial effects from cathodic protection.

5. Reference Cells

Both static and instant-off potentials measured by the reference cells embedded in the seven impessed current systems varied widely from cell to cell, although individual cells responded to current application in a consistent manner. Therefore, the voltage shift between static cell potential and instant-off potential during system operation, rather than the instant-off potential itself, was chosen for comparison with published protection criteria.

A polarization shift between static and instant-off potentials of -100 mV is one of a number of protection criteria described in Reference 7. For Systems 1 to 3, during the initial eight months of operation, the applied current was more than sufficient to satisfy this criterion. Average polarization of the zinc-zinc

sulfate cells in the three systems, for this period, was -230 mV, with values ranging from -187 mV to -301 mV. Polarization levels for the cells in Systems 1 and 3 remained in this range until deterioration of anode connections prevented current flow to all protected areas; this is described in more detail in the Durability section. System 2 experienced lower polarization shifts during hot summer periods when the specified current density could not be maintained because of increased circuit resistance. Control cells installed outside the protected areas, in all three systems, typically showed a gradual cathodic shift in potential during the eighteen months after installation, though the reason for this is not clear.

Polarization shifts seen in Systems 5 to 8 during the first winter months of operation were generally slightly greater than those seen in Systems 1 to 3, averaging -480 mV and ranging between -281 mV and -779 mV. A decrease in polarization was observed in most of the cells as temperatures increased in the spring, leading to an average polarization shift during the April-June period of -243 mV. In System 6 this decrease in polarization was particularly obvious in cells midway between anodes on the long column faces, where polarization shifts were less than -150 mV. Polarization shifts measured by the cells in System 8 during this period were reduced drastically, averaging -164 mV compared to -472 mV during the winter months. This was due in part to the fact that the static potential of cells in this system moved significantly in the negative direction between

winter and summer depolarization periods. This phenomenon was not observed to the same degree in cells in the other systems and the reasons for this difference have not been fully explained.

Considerable variation was seen among the five types of reference cells used. Zinc cells typically exhibited a wide range of values from cell to cell, with individual cells also varying significantly. Zinc cells were placed close to molybdenum cells at two locations. Although initially both pairs of cells showed very similar polarization levels, in the summer months the molybdenum cells indicated a drastically reduced polarization shift while the zinc cells changed very little. The molybdenum cells used often produced an erratic signal and became particularly unstable at temperatures below approximately 5°C. The silver-silver chloride cells also behaved in an erratic manner during periods of low temperatures. Graphite and lead cells appeared relatively stable and consistent over time, showing little variation with temperature or moisture conditions.

Galvanic System

Of the eight installations, the single sacrificial anode system was the one most affected by environmental temperature and humidity changes. Considerable fluctuation occurred on both a seasonal and day-to-day basis. The sum of the currents flowing to each face ranged from low values of 30 - 40 mA, to highs of 100 - 160 mA experienced during the hot summer months of 1983 and 1984. These corresponded to surface current densities in the

range of 1 to 4 mA/m^2, considerably less than experienced in the impressed current systems. The maximum currents were not sufficient to maintain reference cell polarization shifts meeting the protection criteria of -100 mV (7). During periods of very low current flow, the reference cells experienced polarization shifts of only a few millivolts. None of the macrocells consistently experienced reversal of anodic current flow during system activation. Current densities on the pick-up probes were very low. The average current densities on the macrocells and pick-up probes, and the proportion of current flowing to each column face, are shown in Table 2. The typical range of anode-to-rebar resistances is also shown. These resistances varied considerably, but returned seasonally to the same levels. Since the driving voltage of a galvanic protection system is fixed, there is no means of maintaining current levels when circuit resistance increases. The driving voltages of 350 to 400 mV measured offered adequate protection to the steel only when circuit resistance was at a minimum. As noted in Reference 2, the current output of the system was insufficient to meet present protection criteria.

DURABILITY

Although all the impressed current systems functioned satisfactorily from the standpoint of cathodically protecting the steel, some of the components deteriorated in service. The winter of 1983/84 was unusually severe. In addition to prolonged cold spells, there were frequent snowfalls. Deicing salts were rout-

inely applied to the bridge deck with the result that chloride-laden run-off often flowed over the column surfaces below as shown in Figure 10. As a result, the components, especially those on the south column faces, were exposed to numerous freeze-thaw cycles, often in the presence of salt solution.

After eight months of operation, large areas of shotcrete on Systems 1 and 3 were delaminated. Unfortunately, the shotcrete was not checked for delamination after construction so the time of delamination is uncertain. When checked again one year later, the areas of delamination had increased substantially and were cracked extensively. After approximately 5000 amp hours of operation, both systems exhibited a sudden increase in resistance between the anodes and the column reinforcing steel such that the maximum rectifier output of 15 V was no longer sufficient to maintain the current required. Systems 1 and 3 were switched off permanently in April 1984. Figures in Table 2 are based on data collected while the rectifier output remained at 500 mA.

The increased resistance was found to be the result of breakdown of the connections between the lead wires and the polymer concrete anodes. Coring revealed that corrosion had taken place where the copper lead wire was soldered to a short platinized wire protruding from the anode, even though the connections had been sealed. This emphasizes the need for carefully designed and well insulated connections. It may be desirable to keep these connections outside the concrete, where possible, or embed them

within the anode (as was done for the primary anodes in Systems 6 and 7).

System 2 lost large patches of paint during the second winter. The paint peeled cleanly away from the concrete and most of the loss occurred on the south face as shown in Figure 11. As in Systems 1 and 3, the primary anodes showed no damage. Deterioration of the connections was visible and appeared to account for the large increase in the resistance between the middle anode ring and ground. By March 1984, this resistance was so high that current was being distributed only by the top and bottom anode rings. The data in Table 3 summarizes the performance of System 2 prior to March 1984.

There was no deterioration of the shotcrete on System 4. A core taken through an anode after 400 amp hours of operation showed no visible corrosion.

Shotcrete applied to Systems 5 and 7 was sounded 28 days after placement, prior to current application, to determine if debonding of the shotcrete had occurred. The only significant area of debonding (approximately 0.8 m^2) was found on System 5, while System 7 had a few small scattered delaminations. The sounding was repeated in May 1984 after seven months of activation. In both systems, a much greater area of shotcrete was found to be debonded. Minor cracking was seen in the vicinity of the rustication strips and the column corners. Anodes in both systems continued to perform well.

In System 6 there was no evidence of deterioration of either the conductive paint or the polymer and graphite primary anodes after nine months of operation. There was some discoloration and minor cracking of the latex overcoat in the vicinity of the primary anodes.

Gradual deterioration of the conductive paint anode in System 8 contributed to increased circuit resistance and poor current distribution within the protected area. After nine months of operation, approximately 90% of the conductive paint applied to the south face had been lost. Moderate peeling of both paint layers occurred where the conductive paint was applied with an overcoat, or overcoat and tie coat. Deterioration of the conductive paste applied over the platinum wire anodes resulted in portions of the wire being exposed to the environment at several locations. Data shown for this system in Table 3 covers only the period of operation November 1983 - January 1984. During the spring and summer period of 1984, the percentage of current flowing to the west and south faces of the column, where damage is greater, dropped to 24% (from 54% the previous winter). Current density on these faces, which are continuous, was reduced to 6.1 mA/m^2 from 14 mA/m^2.

CONCLUSIONS AND FUTURE WORK

Work in this program to date has indicated that it is possible to design cathodic protection systems which are practical for sub-structure applications. Current levels sufficient to provide

protection to the column rebar can be maintained by suitably designed impressed current systems. Data collected from probes embedded in the test systems indicate that an even distribution of current over the concrete surface can be achieved. Typically, the systems were able to maintain low driving voltages.

Construction and monitoring of these systems has identified several areas where development is required. There is a need for appropriate tests to identify suitable anode materials. Numerous materials are being introduced to the marketplace which appear promising, but no long-term performance data is available. It is necessary to devise accelerated tests which will simulate field conditions to allow prediction of anode service life and failure mode. Reference cells which are stable and reliable must be identified or developed if potential controlled rectifiers are to be practical and dependable for field use. There is also a need to study the durability of alternative connection details and to investigate the reasons for delamination of the shotcrete overcoat in the impressed current systems. Studies in some of these areas have already been initiated.

The next major project in this program will be a larger scale demonstration project applying the most promising of the systems identified so far to a multi-column bridge pier bent. This work is to be undertaken in the fall of 1984.

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Table 1: Summary of Important Features of Systems 1-8

System No.	Primary Anode	Secondary Anode	Overcoat	Area m^2	Type (1)
1	conductive polymer (2)	none	shotcrete	38	I
2	conductive polymer (3)	conductive paint (5)	none	38	I
3	conductive polymer	PAN carbon fiber (S & W faces), pitch carbon fiber (N & E faces)	shotcrete	38	I
4	zinc ribbon	none	shotcrete	38	G
5	conductive polymer mesh (4)	none	shotcrete	45	I
6	conductive polymer (N & W faces) graphite (S & E faces)	conductive paint (5)	latex paint (E & W faces none (N & S faces)	47	I
7	conductive polymer precast (S & E faces), in-situ (N & W faces)	PAN carbon fiber mesh (E,S & W faces), PAN carbon fiber woven with fiber-glass (N face)	shotcrete	47	I
8	platinized wire embedded in conductive paste	conductive paint (5)	none (S face) latex paint (E & W faces) latex paint + tie coat (N face)	33	I

(1) I - impressed current, G - galvanic
(2) carbon fiber core
(3) platinized niobium copper wire core
(4) copper wire core
(5) The three conductive paints had different compositions

Table 2: Systems 1 to 4 - Summary of Current, Current Density and Resistance Data, October 1983 - July 1984

System	Anode or Column Face	Current Density on Concrete (mA/m^2)	Portion of Current Flowing to Each Anode or Face (%)	Average Current Shift during System Operation ($\mu A/cm^2$)			Anode-to-Ground Resistance (Ω)	
				Macrocells		Current Pick-up Probes	High	Low
				W	S			
1	Overall	13.2		-3.4	-2.9	-2.5		
	North face	10.4	12				29	7.7
	South face	14.3	26				34	15
	East face	18.3	35				38	7.1
	West face	13.9	27				46	20
2	Overall	13.2		-2.5	-0.6	-3.5		
	Top ring		35				30	4.2
	Middle ring		45				28	3.9
	Bottom ring		20				32	5.0
3	Overall	13.2		-3.7	-2.2	-5.3		
	East face							
	-anode 1	11.9	6				54	28
	-anode 2		18				26	23
	North face	14.1	17				30	20
	West face							
	-anode 1	16.6	21				18	15
	-anode 2		12				24	18
	South face	14.7	26				22	14
4	Overall	2.1		-0.4		-0.2		
	North face		28				18	2.8
	South face		18				11	1.3
	East face		26				9	2.5
	West face		28				10	3.7

Table 2: Systems 1 to 4 - Summary of Current, Current Density and Resistance Data, October 1983 - July 1984

System	Anode or Column Face	Current Density on Concrete (mA/m^2)	Portion of Current Flowing to Each Anode or Face (%)	Average Current Shift during System Operation ($\mu A/cm^2$)			Anode-to-Ground Resistance (Ω)	
				Macrocells		Current Pick-up Probes	High	Low
				W	S			
1	Overall	13.2		-3.4	-2.9	-2.5		
	North face	10.4	12				29	7.7
	South face	14.3	26				34	15
	East face	18.3	35				38	7.1
	West face	13.9	27				46	20
2	Overall	13.2		-2.5	-0.6	-3.5		
	Top ring		35				30	4.2
	Middle ring		45				28	3.9
	Bottom ring		20				32	5.0
3	Overall	13.2		-3.7	-2.2	-5.3		
	East face							
	-anode 1	11.9	6				54	28
	-anode 2		18				26	23
	North face	14.1	17				30	20
	West face							
	-anode 1	16.6	21				18	15
	-anode 2		12				24	18
	South face	14.7	26				22	14
4	Overall	2.1		-0.4		-0.2		
	North face		28				18	2.8
	South face		18				11	1.3
	East face		26				9	2.5
	West face		28				10	3.7

Table 3: Systems 5 to 8 - Summary of Current, Current Density and Resistance Data, October 1983 - July 1984

System	Anode or Column Face	Current Density on Concrete (mA/m^2)	Portion of Current Flowing to Each Anode or Face (%)	Average Current Shift during System Operation ($\mu A/cm^2$)			Anode-to-Ground Resistance (Ω)	
				Macrocells		Current Pick-up Probes	High	Low
				W	S			
5	Overall	13.5		-5.9	-2.6	-3.2		
	North face	14.8	20				23	4.1
	South face	15.8	21				24	3.5
	East face	14.9	35				15	2.5
	West face	10.1	24				22	3.0
6	Overall	13.3		-7.0	-3.0	-6.1		
	North face	14.1	19				19	4.6
	South face	16.5	22				23	3.4
	East face	12.9	31				21	3.5
	West face	11.7	28				18	3.3
7	Overall	13.2		-3.3	-1.6	-3.4		
	North face	8.0	11				28	6.2
	South face	18.1	24				18	3.9
	East face	12.4	30				23	4.0
	West face	14.5	35				15	2.7
8	Overall	13.1		-4.8	-0.7	-5.2		
	North face	12.2	18				9.4	4.9
	East face		28				7.4	3.9
	South face	14.2	23				30	3.4
	West face							
	-north		14				24	5.2
	-south		17				14	3.7

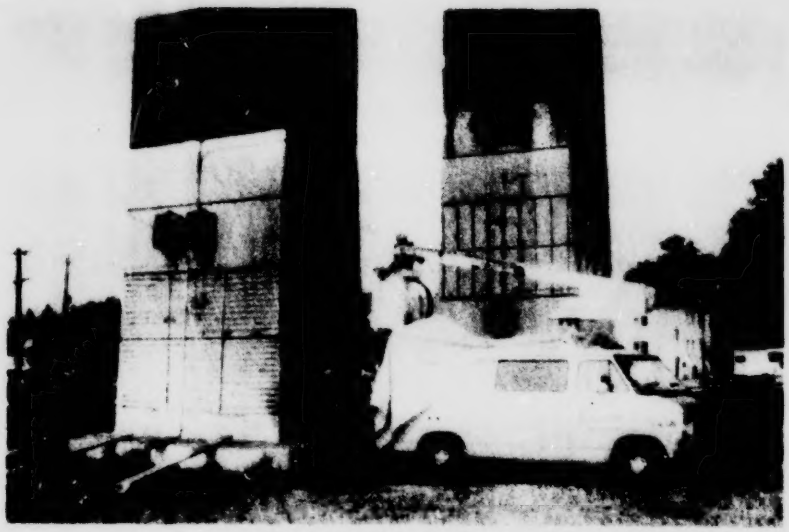

Figure 1/ Systems 1, 2, and 3 under Construction, August 1982 System 1 is on the right column; Systems 2 (upper) and 3 (lower) are on the left column.

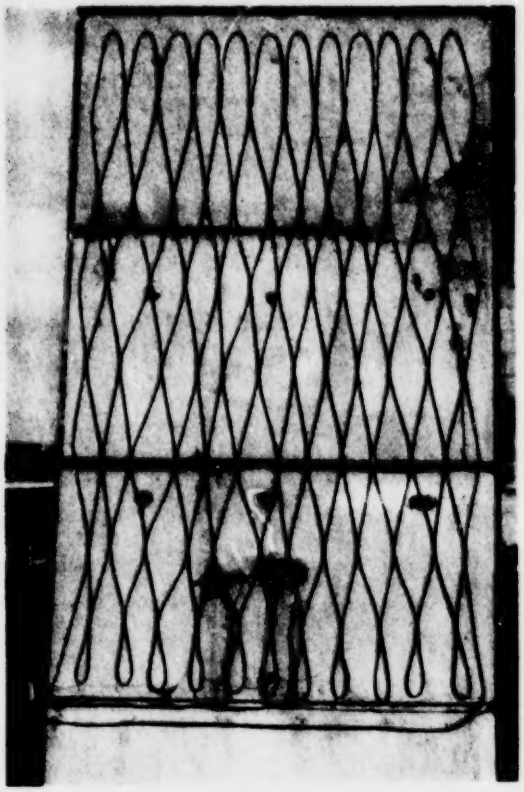

Figure 2/ System 5 – South Face
The expandable anode mesh is shown prior to shotcreting.

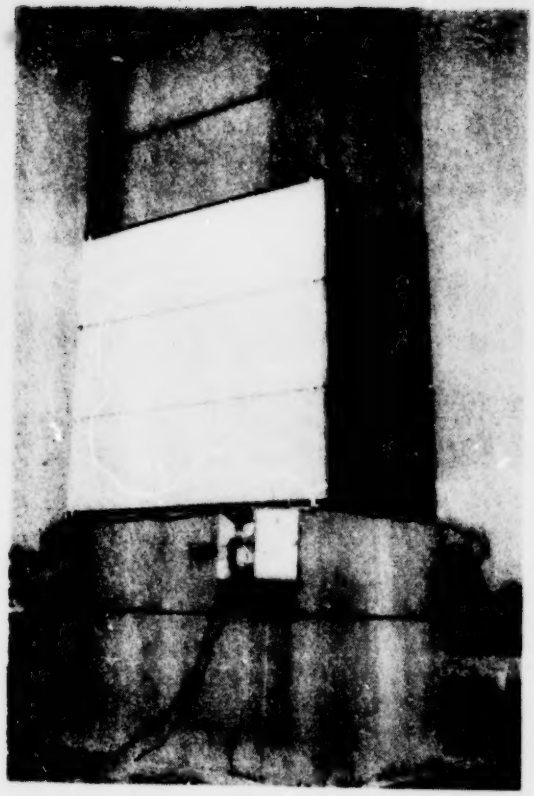

Figure 3/ System 6
The south face (with exposed conductive paint) and the west face (with a latex overcoat on the conductive paint) are shown.

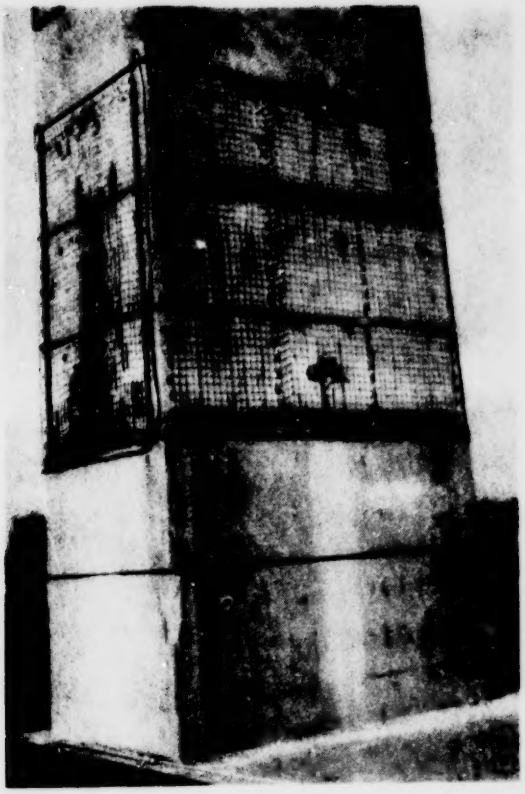

Figure 4/ System 7
Primary and secondary anodes on the south and east faces are seen prior to shotcreting.

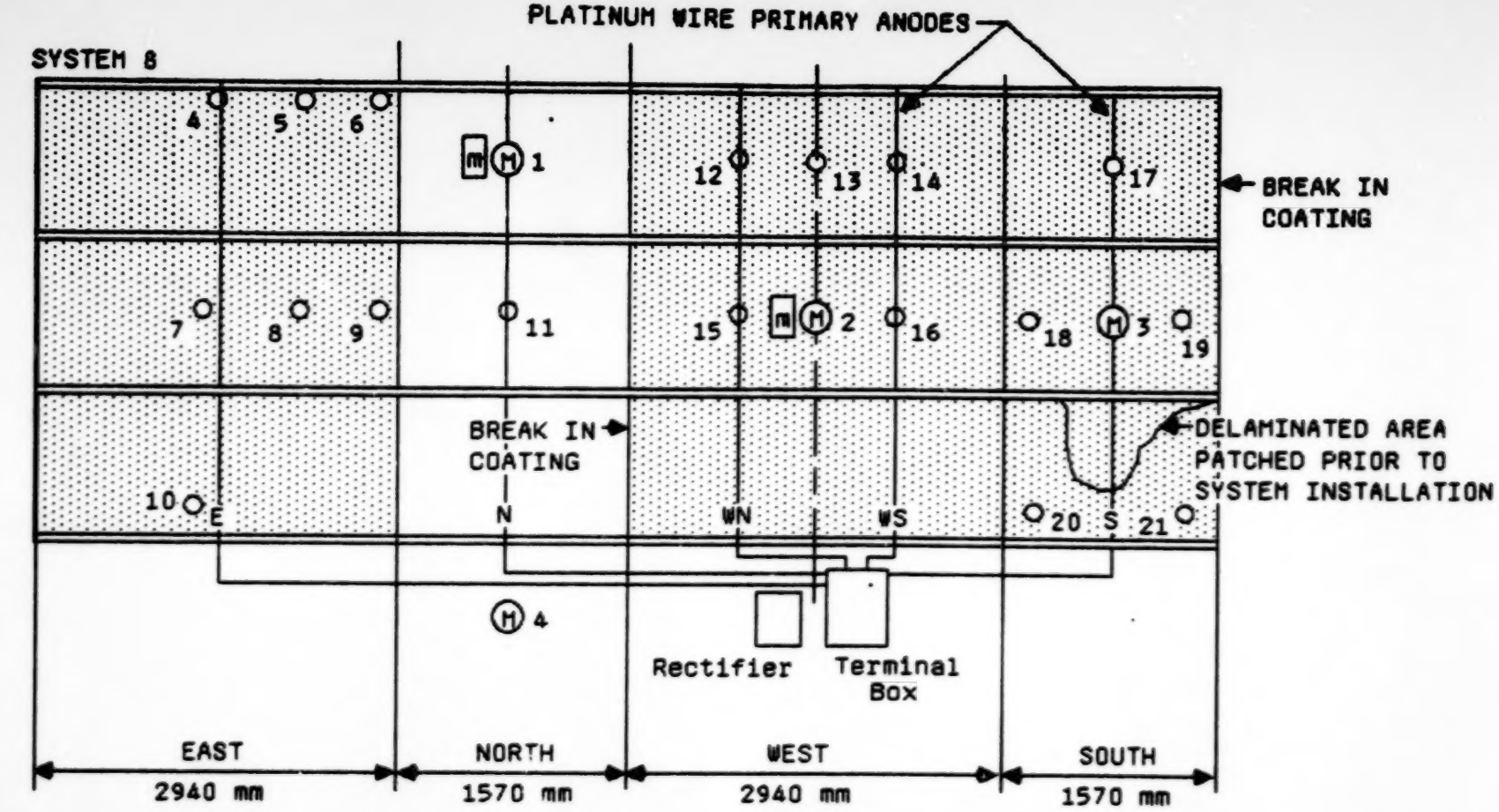

Figure 5/ System 8 — Anode and Instrumentation Placement

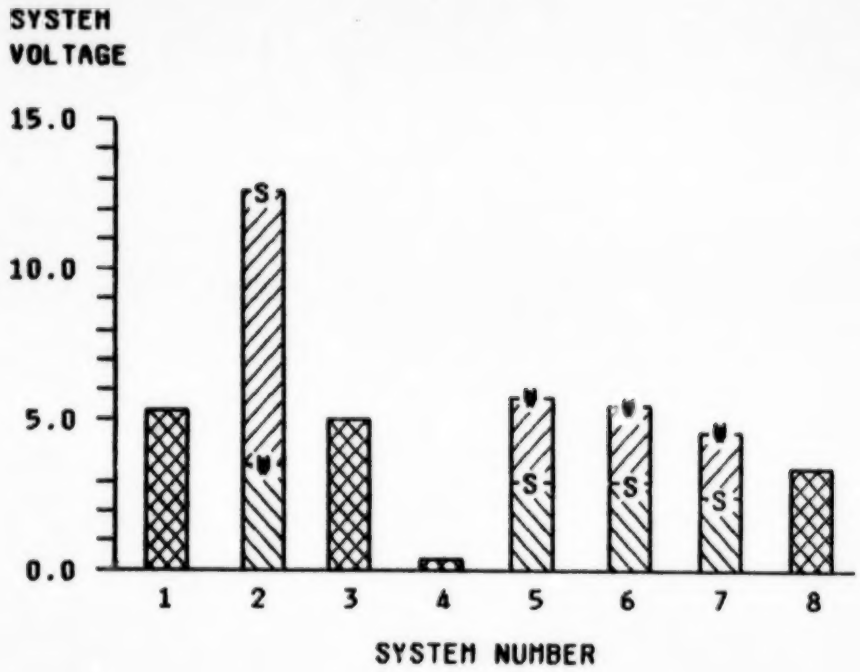

Figure 6/ Typical Operating Voltages for Systems 1 to 8
W and S denote winter and summer periods of operation respectively.

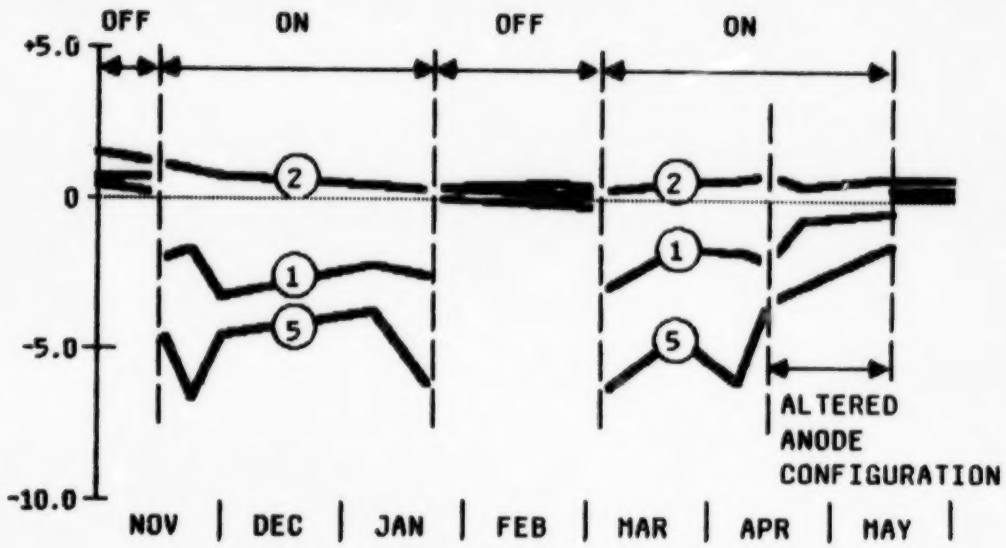

Figure 7/ System 2 – Current Density on Macrocell Probes 1,2 and 5 During the Period November 1982 – May 1983

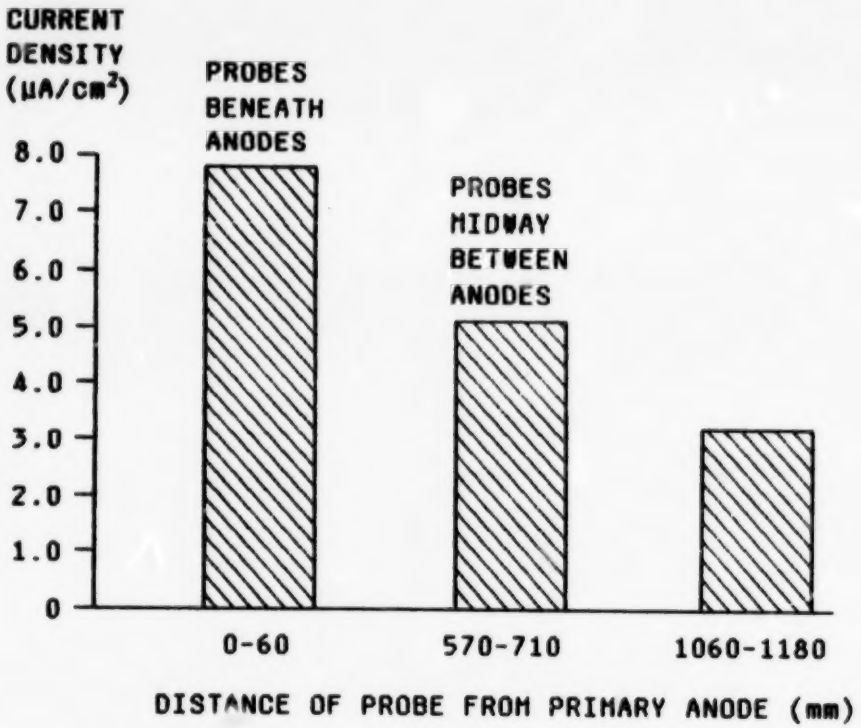

Figure 8/ System 3 – Variation of Probe Current Densities with Distance from Primary Anode

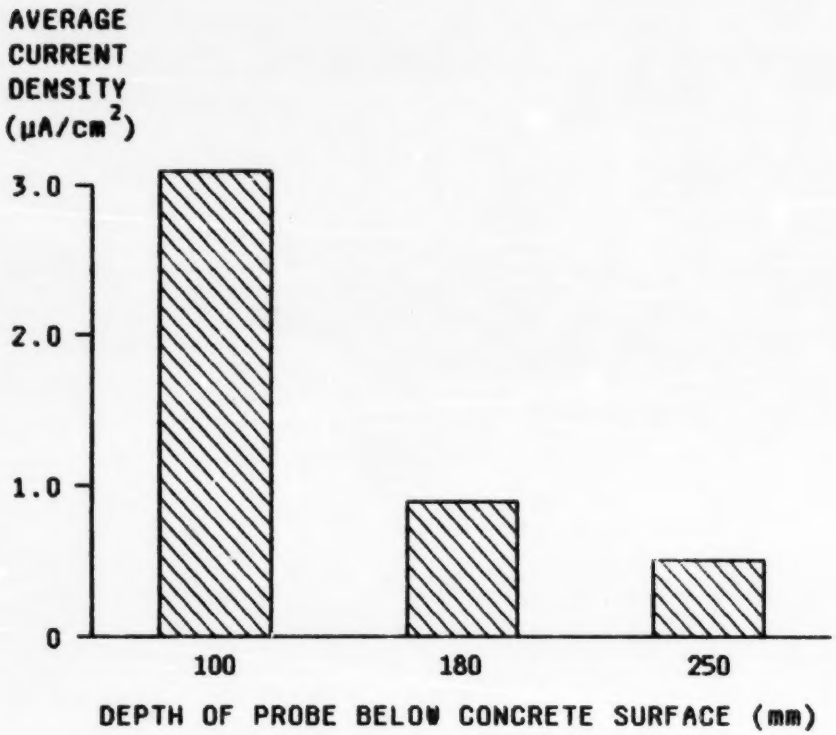

Figure 9/ Current Distribution Probes, System 1, 2 and 3 Average Current Received by Probes at 100, 180 and 250 mm depths below Concrete Surface

Figure 10/ Typical Exposure Conditions of Columns during the Winter Months (System 6 shown)

Figure 11/ System 2
Deterioration of conductive paint on the south column face, 15 months after application.